# A 700 YEAR-OLD PULSAR IN THE SUPERNOVA REMNANT KES 75

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## ABSTRACT

Since their discovery 30 years ago, pulsars have been understood to be neutron stars (NSs) born rotating rapidly ($\sim 10-100$ ms). These neutron stars are thought to be created in supernova explosions involving massive stars, which give rise to expanding supernova remnants (SNRs). With over 220 Galactic SNRs known (Green 1998) and over 1200 radio pulsars detected (Camilo et al. 2000), it is quite surprising that few associations between the two populations have been identified with any certainty. Here we report the discovery of a remarkable 0.3 sec X-ray pulsar, PSR J1846−0258, associated with the supernova remnant Kes 75. With a characteristic age of only 723 yr, consistent with the age of Kes 75, PSR J1846−0258 is the youngest pulsar yet discovered and is being rapidly spun down by torques from a large magnetic dipole of strength $\simeq 5\times10^{13}$ G, just above the so-called quantum critical field. PSR J1846−0258 resides in this transitional regime where the magnetic field is hypothesized to separate the regular pulsars from the so-called magnetars. PSR J1846−0258 is evidently a Crab-like pulsar, however, its period, spin-down rate, spin-down conversion efficiency, are each an order-of-magnitude greater, likely the result of its extreme magnetic field.

*Subject headings:* pulsars: individual (PSR J1846−0258); supernova remnants: individual(Kes 75); star: individual (AX J184624.5−025820); stars: neutron, magnetars; X-rays: general

## 1. INTRODUCTION

Kes 75 (also G29.7−0.3) is one of the few examples in our Galaxy of a young, shell-type remnant ($3.5'$ in diameter) with a central core ($30''$) whose observed properties suggest a synchrotron plerion similar to the Crab Nebula (Becker & Helfand 1983; Becker, Helfand & Szymkowiak 1983; Blanton & Helfand 1996). It has long been suspected that this bright core component of Kes 75 might harbor a young pulsar, given its strong radio polarization and flat spectral index, but none had been detected in any wave-band (Becker, Helfand & Szymkowiak 1983). We have observed the region around this supernova remnant several times with the X-ray detectors aboard the Rossi X-ray Timing Explorer (*RXTE*), while targeting a nearby anomalous X-ray pulsar, and identified coherent pulsations at a period of 0.32456 s. Since *RXTE* is a non-imaging instrument only crude directional information was available. Subsequent examination of archival data from the Advanced Satellite for Cosmology and Astrophysics (*ASCA*) allowed us to locate the pulsed emission to the core of the Kes 75 remnant. With five period measurements spanning seven years, we are able to derive a stable period derivative. The analysis of these data and the results they imply are the subject of this Letter.

## 2. OBSERVATION AND ANALYSIS

The main instrument on-board the *RXTE* observatory (Bradt, Rothschild & Swank 1993) consists of five co-aligned collimated detectors known collectively as the Proportional Counter Array (PCA; Jahoda et al. 1996). The effective area of the combined detector is about 6500 cm$^2$ at 10 keV with a roughly circular aperture response of $\sim 1^\circ$ FWHM. Moderate spectral information is available in the $2-60$ keV energy band with a resolution of $\sim 16\%$ at 6 keV. The absolute timing uncertainty is $\sim 100$ $\mu$s (Rots et al. 1998). The arrival time of each photon was corrected to the Solar System barycenter using the JPL DE200 ephemeris. An Observation Log giving the net observing times is presented in Table 1.

The discovery of the 0.3 s pulsation was made using $2^{22}$-bin Fast Fourier transforms on our Jan 2000 data set (see below). This produced a significant coherent signal at $\simeq 0.32456$ s. No higher harmonics were found. We next folded the timeseries into 20-bin periodograms centered near 0.3246 s; a large deviation from a uniform model was found at a period of $P = 0.3243870$ s ($\chi^2 = 220$; April 1999), $P = 0.3245634$ s ($\chi^2 = 300$; Jan 2000), and $P = 0.3246446$ s ($\chi^2 = 700$; June 2000). With these three observations, we were able to interpolate a preliminary period derivative of $\dot{P} = 7.1\times10^{-12}$ s s$^{-1}$.

We then examined archival data of the region acquired by the *ASCA* observatory (Tanaka, Inoue & Holt 1994). Two observations were available with sufficient duration and time resolution for a pulsar search; of these, one is a deep 45 ks *ASCA* pointing centered on Kes 75 whose analysis is detailed in Blanton & Helfand 1996. We searched data obtained with the Gas Imaging Spectrometer (GIS) for evidence of pulsed emission around the period extrapolated from the *RXTE* observations assuming a constant period derivative. A total of 12,800 photons from the two GISs were extracted from a $8'$ diameter aperture restricted to the hard energy range of $3-10$ keV. The selection of

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the hard energies pre-filters the softer background emission from the SNR. Photon arrival times were again corrected to the Solar System barycenter and then folded into periodograms in order to search for a coherent signal. A faint but unmistakable signal ($\chi^2 = 70$ for 10 phase bins) was found at the expected period. This result was reproduced ($\chi^2 = 40$ for 10 phase bins) in the second *ASCA* observation of 28 Mar 1999 which contained the SNR in the field-of-view, $22'$ off-axis.

**Figure 1** — The *ASCA* broad-band X-ray image (greyscale) of the region containing the supernova remnant Kes 75. The overlayed contour plot shows the pulsed emission component from PSR J1846−0258, locating the pulsar to the core of Kes 75. The images are scaled by the square root of the intensity while the contours are spaced in 10% increments.

To demonstrate that these pulsations are uniquely associated with Kes 75, we performed phase-resolved image analysis as described in Gotthelf & Wang (2000). We generated images of the pulsed emission by subtracting the off-pulse data from the on-pulse image. Only a single source of significant emission remained: the pulsed emission, an unresolved *ASCA* point-like source located at the coordinates of the SNR Kes 75 (see Figure 1). We thus unambiguously locate the origin of the pulsed emission to within an arcminute of the center of Kes 75.

Next, we used the *ASCA* imaging data from the Solid-state Imaging Spectrometer (SIS) to further refine the source location within the SNR. The X-ray emission from Kes 75 is known to have two components (Blanton & Helfand 1996), i.e. softer thermal emission of the shocked interstellar medium of the SNR shell which cuts off above 3 keV, and a hard component with a power-law spectrum which is unresolved with *ASCA* imaging and is located within the boundaries of the SNR. This hard source, presumably due to non-thermal emission by confined relativistic particles, was thought to contain the pulsar and possibly an extended plerionic nebula. The SIS coordinates of the hard point source, the putative pulsar, are R.A. $18^h46^m24.5^s, Dec. -02°58'28''$ (J2000) with an uncertainty of $12''$ after correcting for the *ASCA* temperature variation by the method of Gotthelf et al. (2000) This position lies within $10''$ of the center of the Crab-like emission in the middle of the radio remnant (Becker, Helfand & Szymkowiak 1983).

Employing the new localization, we re-barycentered all 5 observations and re-determined the pulse periods using the trial period derivative. A least-square fit of these period measurements to a constant spin-down model gives an ephemeris for the Kes 75 pulsar with period $P = 0.32359795 \pm 0.00000012$ s and period derivative $\dot{P} = 7.09706 \pm 0.00094 \times 10^{-12}$ s/s, referenced to epoch MJD 50000.0. We also fitted the data points to a spin-down model with a second period derivative term. Although the fits to both models were found to be statistically acceptable with $\chi^2_\nu \lesssim 1$, it was not improved by adding the second derivative. Figure 2 shows the period evolution and the residuals from the best-fit linear model; our estimates of the period uncertainty for each data point in Figure 2 are derived by using the method of Leahy (1983). We find no evidence of period glitches in our measurements, as are frequently observed in other young rotation-powered pulsars; however, considering the sparse sampling they are by no means ruled out. A summary of the timing results for each data set used in this study is given in Table 1.

**Figure 2** — The pulse period evolution of PSR J1846−0258. (Left) Displayed are the period measurements along with the best fit to a linear spin-down model (see text). (Right) The residuals from this fit are shown along with their 1-$\sigma$ uncertainty error bars computed using the method of Leahy (1987). The pulsar is evidently undergoing steady spin-down at a rapid rate with no significant timing noise or noticeable glitch activity.

Using the above ephemeris, we generated pulse profiles for the *ASCA* and the *RXTE* combined data sets. These profiles are displayed in Figure 3. They are well characterized by a single, broad peaked pulse with a $\sim 50\%$ duty cycle. The profiles appear similar. The pulsed emission comprises 5.5% of the total *ASCA* counts in the background-subtracted folded light curves, suggesting that steady emission from a synchrotron nebula might be dominating the flux. This is the same fraction as measured for the Crab pulsar (Seward 1984).

The *ASCA* spectrum of Kes 75 with its hard non-thermal component is presented in Blanton & Helfand (2000). We have analyzed the *RXTE* spectrum of the system above 3 keV so as to exclude remnant's thermal emission. The $3-20$ keV *RXTE* spectrum was fitted to an absorbed power law model with an absorbing column of $\mathrm{N}_H = 3.1 \times 10^{22}$ cm$^{-2}$, the *ASCA* value, and used the standard background model along with a Gaussian line at 6.5 keV corresponding to the Galactic Ridge diffuse Fe emission. We obtained a good fit for a photon index $\Gamma = 2.18 \pm\ 0.04$ ($\chi^2_\nu = 1.4$), typical of a young, Crab-like pulsar and consistent with the *ASCA* value. The unabsorbed flux from the pulsar plus synchrotron nebula emission is $1.8 \pm\ 0.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Next, we considered the spectrum of the pulsed emission alone by analyzing phase dependent spectra. Using the off-pulse spectrum as background, we measure a hard photon index $\Gamma = 1.1 \pm\ 0.3$ ($\chi^2_\nu = 1.5$) with an unabsorbed flux of the pulsed component of $0.96 \pm\ 0.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the $3-10$ keV energy band.

**Figure 3** — The pulse profile of young pulsar PSR J1846−0258 in the $3-10$ keV band from the *RXTE* (top) and *ASCA* (bottom) observations folded into 20 phase bins using the ephemeris presented in the text. The two profiles have been aligned to place the peaks at the 0.5 phase bin; the relative phases are arbitrary. The profiles include 105 ks and 93 ks of *RXTE* and *ASCA* data, respectively.

## 3. DISCUSSION

The steady increase in the period suggests a constant energy loss at a rate of $\dot{E} = (2\pi)^2 I\dot{P}/P^3 \simeq 10^{37} I$ ergs s$^{-1}$, where $I$ is the NS moment of inertia in units of $1.4 \times 10^{45}$ g cm$^2$. In the standard pulsar model of a rotating magnetized dipole, spin-down energy is lost via magnetic dipole radiation, $\dot{E} \sim (B_p^2 R^6 \Omega^4)/(6c^3)$. This model assumes a braking index of 3 and a uniformly magnetized stellar interior. From the above relationships we can infer the surface magnetic field at the pole, which, for PSR J1846−0258, gives $B_p \simeq 4.8 \times 10^{13}$ G. Here, $R \sim 10$ km is the neutron star radius, $\Omega = 2\pi/P$ is the angular velocity of the rotation, and $c$ is the speed of light *in vacuo*. The characteristic spindown age ($\tau = P/2\dot{P}$) of PSR J1846−0258 is $\simeq 723$ yr, the youngest characteristic age of any known pulsar.

For a well-behaved Crab-like pulsar with a braking index similar to 3, the spindown age is reasonably consistent with that reported for Kes 75 itself. Blanton & Helfand (1996) estimated the age of the remnant to lie between 900 and 4,300 years, based on free expansion and Sedov phase estimates, respectively. They preferred a value closer to $10^3$ years, while arguing that the remnant was still in free expansion phase, giving an age $\tau \sim 900 d_{19} v_5^{-1}$ years. Here, the distance to the SNR is $19 d_{19}$ kpc (Milne 1979) and the free expansion velocity is $5000 v_5$ km s$^{-1}$. Given the quality of age estimators, the two limits are consistent. Finally, we note that the cumulative energy in particles and fields within the plerion – a calorimetric measure of the pulsar's activity – is estimated from radio observations to be $10^{48} d_{19}^{17/7}$ erg (Blanton & Helfand 1996). This is also consistent with the lower limit derived from the age of the pulsar and its current spin-down loss, $\tau\dot{E} \sim 3 \times 10^{47}$ erg. From the spin properties and location of PSR J1846−0258 we infer an extremely young and highly magnetized pulsar associated with the SNR Kes 75.

At the assumed distance to the SNR, the total X-ray luminosity from the pulsar plus synchrotron nebula is $7.8 \times 10^{35} d_{19}^2$ erg s$^{-1}$ in the $3-10$ keV band; for comparison, this translates to $2.1 \times 10^{36}$ erg s$^{-1}$ in the ROSAT $0.1-2.4$ keV band for the spectral parameters given above. The X-ray luminosity of this region was already found to be the among the highest of any of the Crab-like SNRs, and second only to the Crab itself, depending on the true distance. The derived pulsed luminosity of $4.1 \times 10^{34} d_{19}^2$ erg s$^{-1}$ ($3-10$ keV) suggests that $\sim 4 \times 10^{-3}$ of the pulsars spin-down energy is emitted as pulsed X-rays in the $3-10$ keV band or $\sim 1 \times 10^{-3}$ in the $0.1-2.4$ keV. This value is similar to those observed from other rotation powered pulsars (Becker & Trümper 1999) and suggests that particle acceleration is occurring in the NS magnetosphere. However, the ratio of the total pulsar plus nebula luminosity to the spin-down energy loss is $6 d_{19}^2$ times greater than that for the Crab pulsar.

In many ways, PSR J1846−0258 resembles any other rotation-powered Crab-like pulsar; however, its period, spin-down rate, spin-down conversion efficiency, and inferred magnetic field, are each an order-of-magnitude greater. The timing parameters of the new pulsar are most similar to the young 0.4-s pulsar J1119−6127 with its period derivative of $4.0 \times 10^{-12}$ s/s implying $B_p = 4.1 \times 10^{13}$ G. This pulsar, though 4 times closer, does not contain a similar bright radio or X-ray plerion (Camilo et al. 2000).

Recent research suggests that young neutron stars may have at least two distinct evolutionary branches (see Gotthelf & Vasisht 2000 and refs. therein). Besides the Crab-like pulsars which evolve through magnetic braking, with fields in the range $10^{12} - 10^{13}$ G and spin periods at birth of order 10 ms, a second branch is made up of the anomalous X-ray pulsars (AXPs; Mereghetti & Stella 1998 and refs. therein; Duncan & Thompson 1996) and the soft $\gamma$-ray repeaters (SGRs; Cline et al. 1982; Kulkarni & Frail 1993), likely "magnetars", with magnetic fields in the range $10^{14} - 10^{15}$ G (Vasisht & Gotthelf 1997; Kouveliotou et al. 1998). The magnetars typically have long spin periods, and their steady emission has only been observed in the X-ray band. The new pulsar PSR J1846−0258 lies in a transitional regime with $B_p \simeq 5 \times 10^{13}$ G.

Few regular pulsars have implied magnetic fields strictly above the quantum critical field, $B_{cr} \simeq 4.4 \times 10^{13}$ G; in fact, the only such pulsar known thus far is the radio pulsar PSR J1814−1744 which has an inferred field of $B_{13} \simeq 5.5$ (Pivavoroff, Kaspi & Camilo 2000; Camilo et al. 2000), just above this limit. Free electrons gyrate relativistically in $B > B_{cr}$ with radii less than the electron Compton wavelength, $\hbar/m_e c$. In regular pulsars such as the Crab and Vela the purely quantum process of single photon pair-production $\gamma \rightarrow e^+e^-$ is invoked as a source of particle acceleration (Sturrock 1971). It has been suggested that for magnetars with $B > B_{cr}$, the quantum electrodynamical process of photon splitting ($\gamma \rightarrow \gamma\gamma$), may compete with pair production and act as a quenching mechanism for electrons, and suppress radio emission (Baring & Harding 1998). Note that the large pulse duty cycle in PSR J1846−0258 suggests that unlike the Crab, which has a sharp high-energy pulse, the X-ray producing particles in this pulsar are largely in the outer magnetosphere. Also, it remains to be seen if PSR J1846−0258 is detectable as a radio pulsar. The shape of the radio pulse profile, vis-a-vis the X-ray pulse would also be of considerable interest.

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Table 1
Observation Log of Kes 75

| Mission | Date[a] (UT) | Epoch (MJD) | Exposure/ Duration (ks) | Period (s) | Uncertainty (ns) | Offaxis[b] (arcmin) | Pulsed Flux[c] $\times 10^{-12}$ (ergs cm$^{-2}$ s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| *ASCA*... | 1993 Oct 10 | 49273.045014 | 44.5/86 | 0.32315219 | 200.0 | 7 | 1.2 |
| | 1999 Mar 28 | 51265.924020 | 48.7/140 | 0.32437427 | 100.0 | 20 | ... |
| *RXTE*... | 1999 Apr 18 | 51286.667628 | 27.6/120 | 0.324386957 | 80.0 | 23 | 0.6 |
| | 2000 Jan 30 | 51574.527481 | 39.6/140 | 0.324563369 | 60.0 | 23 | 0.8 |
| | 2000 Jun 11 | 51706.829628 | 37.7/88 | 0.324644591 | 50.0 | 0.1 | 1.0 |

[a]For the start of the observation.

[b]Distance of Kes 75 from the obsevatory pointing direction.

[c]The unabsorbed pulsed *RXTE* and *ASCA* flux using an absorbed power law model of photon index 1.1, in the $3-10$ keV energy band. The *ASCA* GIS flux is derived using photons extracted from $4'$ radius aperture centered on the *ASCA* Kes 75 position. The off-pulse spectrum was used as a background. See text for details.